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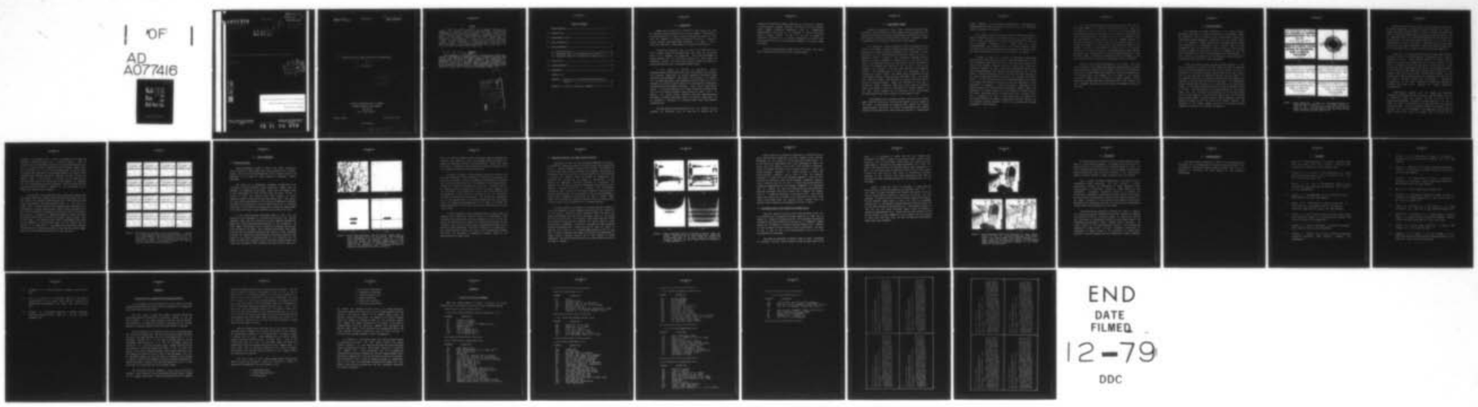

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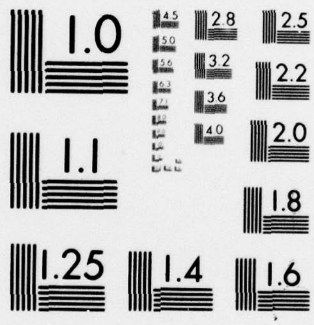
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INTERACTIVE DIGITAL IMAGE RESTORATION AND ENHANCEMENT

J.F. Boulter

Centre de Recherches pour la Défense
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(6) INTERACTIVE DIGITAL IMAGE RESTORATION AND ENHANCEMENT

by

(10) J. F. Boulter

(11) Jul 79

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RESUME

On décrit un système interactif de traitement numérique des images. Ce système comprend un mini-ordinateur, un processeur programmable de tableau et de l'équipement en direct servant à la digitalisation et à l'affichage des images. L'utilisation de ce système pour la reconstitution et l'amélioration des images est expliquée. On analyse une photographie floue prise avec une caméra hors de focalisation pour déterminer la nature du flou, puis on reconstitue l'image. On procède également à l'amélioration des images de types spectre visible, infrarouge, et radiographique en utilisant des techniques fondées sur des caractéristiques du système visuel humain et sur le processus de formation des images. (NC)

ABSTRACT

THIS REPORT DESCRIBES ~~We describe~~ an interactive digital image-processing system that includes a minicomputer, a programmable array transform processor and on-line image digitizing and display equipment, and illustrate typical applications in the areas of image restoration and enhancement. A photograph blurred by a defocused camera is analyzed to determine the nature of the blur and is restored. Image-enhancement techniques, based on the properties of human vision or on the image-formation process, are applied to visible light, infrared and radiographic images. (U)

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1.0 INTRODUCTION

Images that are defective or deficient in some respect can often be improved through processing with a digital computer. The purpose of the processing may be to remove a specific degradation, motion or focus blurs for example, or to enhance information of interest. In general, current automatic image-improvement techniques (e.g. Refs. 1 and 2) cannot yet equal what a human operator can achieve interactively.

Interactive processing puts the man "in the loop" where he is able to rapidly inspect the processed image and apply new processing based on his judgement and experience. The recent development of digital hardware that can efficiently process the large amount of information present in a typical high-resolution image, now makes this processing practical with a minicomputer-based system.

In this report, we describe an interactive digital image-processing system based around a PDP 11/40 computer and illustrate its processing capabilities by giving examples of interactive image restoration and enhancement. The system is not limited to its present role of image improvement (some examples are given in Refs. 3-7) but is intended as a flexible research facility for investigating 2-dimensional signal-processing and display techniques. Other current applications include a real-time simulation of a target correlation tracking system (Ref. 8) and a study of automatic target acquisition (Refs. 9-11). In general, the system permits potential real-time image-processing techniques, including those which require less operator supervision, to be evaluated or optimized by simulation before their final hardware implementations.

The experimental system described in Sec. 2.0 includes on-line equipment for digitizing film, for real-time TV display and for

recording on Polaroid film images containing up to 512 by 512 elements. A special-purpose hardware processor interfaced to the host computer allows complex processing operations, such as 2-dimensional frequency-domain filtering, to be performed on 256- by 256-element images in several seconds. In Sec. 3.0, we give an example of interactive restoration of a blurred photograph by inverse Wiener filtering and in Sec. 4.0, we show several examples of interactive image enhancement.

This work was performed at DREV during 1977-78 under PCN 33A40, Digital Image Processing and PCN 21J03, Imaging Seekers.

2.0 EXPERIMENTAL SYSTEM

Effective interactive digital image processing requires rapid processing, flexible methods for controlling the various operations, and convenient facilities for viewing and permanently recording the results. The filtering or display operations that we use most frequently should be completed, and the results viewed, within a few seconds.

Our interactive system is based on a PDP 11/40 computer with 24 kwords of core memory. Image processing and image input or output (I/O) operations are controlled through commands given on a teletype. A brief description of the image-processing operating system is given in Appendix A while a listing of the interactive commands currently available is given in Appendix B. Options, such as the size of the image to be processed (128 by 128, 256 by 256 or 512 by 512 elements), or that of the display area (128 by 128, 256 by 256 or 512 by 512 elements), are selected by setting sense switches on the computer console. Film transparencies or prints are digitized with a high-quality vidicon scanner (ITM Model 201/E) interfaced to the PDP 11/40 computer through a video digitizer (CVI Model 270). An analog scan conversion memory (PEP Model 400) driving a 1225-line TV monitor provides a real-time display. Images are recorded on film with a flying-spot scanner (Tektronix Model 602 or 606) viewed by a Polaroid camera. The system is linked to a Honeywell 560 digital computer, an EAI 8845 hybrid computer and an Optronics P-1700 rotating-drum microdensitometer/film writer through a 9-track magnetic tape.

A programmable array transform processor (Floating Point Systems Model AP120-B) interfaced to the PDP 11/40 computer is a key element of the system. It has decreased the computing time required for typical image-processing operations by a factor of approximately 300, allowing complex filtering operations, which previously required a medium-scale

digital computer, to be performed interactively. For example, the 2-dimensional fast Fourier transform (2D FFT) of a 256- by 256-element image is performed in 1.4 seconds.

One usually uses an interactive system to process images with a spatial resolution of 512 by 512 elements or less. In such cases, a vidicon camera designed for high gray scale and geometric accuracy can be an acceptable alternative to a slower and more costly microdensitometer for digitizing film. In a vidicon system, we select the region of the film to be digitized by adjusting the camera optics and film position while we view the camera output on a TV monitor.

Provided at least 10 TV frames are averaged to sufficiently reduce vidicon noise, the camera yields a gray scale resolution of 0.03D over the density range 0-3D. Noise due to film granularity exceeds this level at most effective sampling apertures and we have found this resolution adequate for many deblurring or enhancement applications. The main disadvantages of the vidicon digitizing system are its limited number of spatial-resolution elements, the long-term image retention by the vidicon target and the need to calibrate the spatial and density scales. On the other hand, unlike most microdensitometers, the optics of the camera lens and the illumination system can be adjusted to allow measurement of specular or diffuse film density. Measurement of the specular density of a silver halide film produces a sharper image than measurement of diffuse density but at the expense of a higher level of film noise. When noise due to film granularity is the limiting factor (as is frequently the case in image deblurring or enhancing of low-contrast details, for example), measurement of diffuse density may be preferred, whereas specular density may be preferred for optimum enlargement of small details.

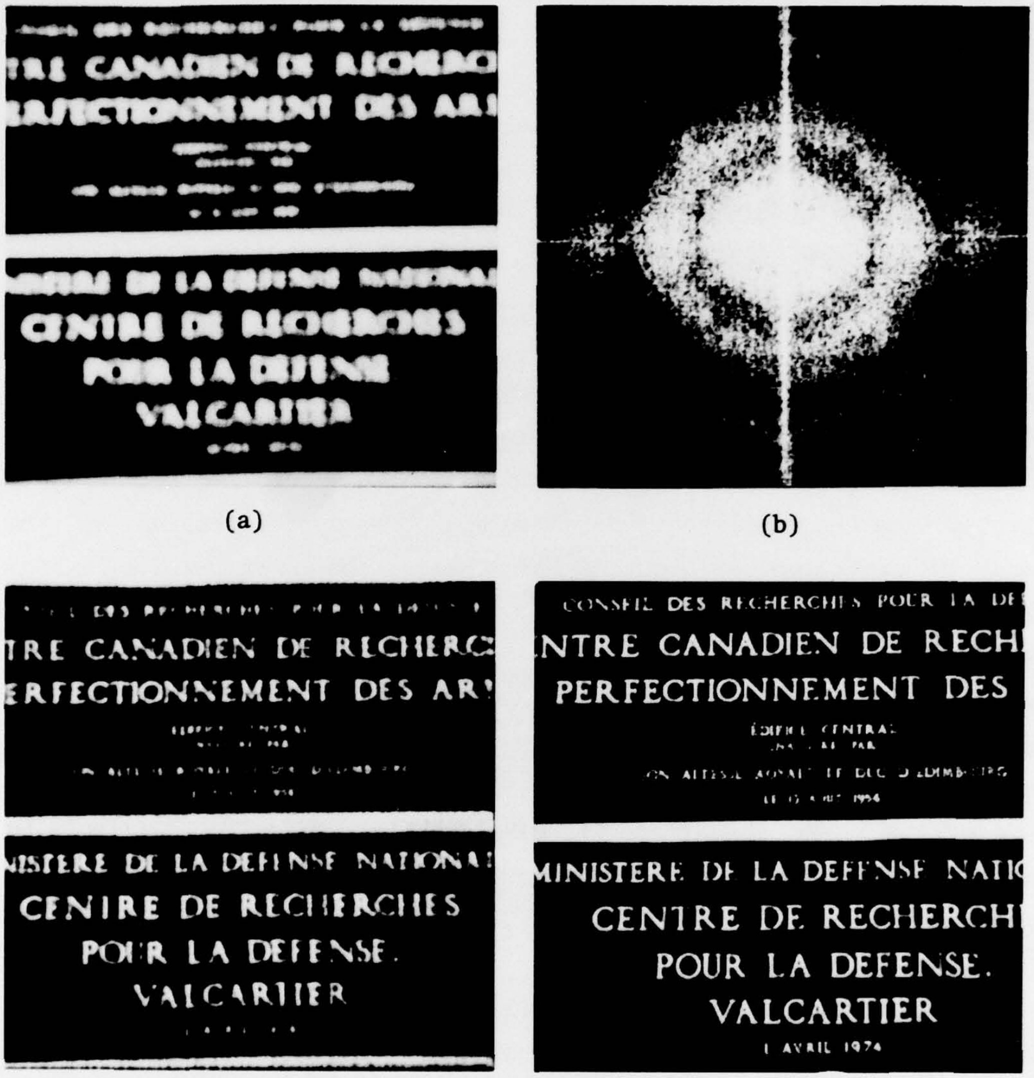
The array transform processor processes the images under control of the host computer. In a typical filtering operation, the image (or one quarter of it, in the case of a 512- by 512-element image) is transferred from an RK05 disk memory to the 65 kword data memory of the array transform processor. High-speed disk I/O routines (Ref.12), which are approximately 10 times faster than the standard Fortran I/O routines, were written and these allow 65 thousand 16-bit words to be transferred between a disk and the array processor data memory in 1.4 seconds. The image is then processed at a rate of up to 12 million operations per second according to algorithms which the host computer has placed in the program memory of the array transform processor. The processed image is scaled and returned to a disk or displayed. A 256- by 256-element image is displayed or recorded on film in 2.5 seconds.

We plan to make several improvements in the system. The gray scale resolution of the analog scan conversion display memory is limited and degrades after about 15 min of readout. This will be replaced by a digital color display system with graphics and interactive capabilities. A time-shared PDP 11/70 computer will be added to the system. Low-priority tasks, such as editing or linking programs, will be performed at the same time that a "privileged" user, who controls the array transform processor and on-line image I/O equipment, operates in real time.

3.0 IMAGE RESTORATION

The objective of image restoration is to remove a specific degradation and restore, as closely as possible, to some "ideal" image. The degradation may be caused by the imaging process itself (e.g. transmission through atmospheric turbulence), by the imaging system (e.g. an improperly focused camera) or by the image-recording medium (e.g. nonlinearity of photographic film). Typical types of image degradations that one can restore include blurring (e.g. due to motion or focus), geometrical distortion (e.g. due to perspective) and gray scale nonlinearity (e.g. due to film overexposure or underexposure). In this section, we illustrate the use of interactive image processing to identify and remove focus blur from a photograph.

Figure 1(a) shows an image, recorded on Kodak Panatomic X film, which was blurred in a camera. We first analyze the image to determine the type of blurring (motion, focus, etc.) and its extent. This can be described by the optical transfer function (OTF) of the blur. Gennery (Ref. 13) has shown that the modulation transfer function (MTF), i.e. the modulus of the OTF, of a spatially invariant blur can frequently be observed in the power spectrum of the blurred image. If the MTF pattern contains characteristic structures (e.g. zeros) which are sufficiently visible in the power spectrum, then this can help to determine the OTF of the blur. The ring structure in the power spectrum of the present image (Fig . 1(b)) is typical of blurring due to an out-of-focus camera with a circular aperture. The OTF of this type of blur is a first-order Bessel function (Refs. 1 and 14), and the 2 minima observed in the power spectrum correspond to the first 2 zeros of the Bessel function. The positions of the minima estimate the blur circle to have an average diameter of 0.68 mm on the original film negative.



(a) (b)

(c) (d)

FIGURE 1 - Image deblurring. A region of a photograph blurred in a defocused camera is shown in (a). Its power spectrum is given in (b). In (c) we have restored the blur by inverse Wiener filtering. The same region of the sign taken with the camera correctly focused is given in (d).

Before performing the restoration, we first match the gray levels of opposite edges over a 3-element wide region bordering the image to reduce artifact generation (Refs. 6, 7 and 15). Then, we calculate the 2D FFT of the image, multiply by the inverse Wiener filter (Refs. 7 and 14) generated using the above Bessel-function OTF, and calculate the inverse 2D FFT. The resulting restored image (Fig. 1(c)) is much less blurred than the original; text which is illegible in the original image can easily be read after restoration. Figure 1(d) shows the same region of the sign taken with the camera correctly focused for comparison.

Noise due to film granularity and, to a lesser extent, spatial variance of the blur, limited the amount of restoration that could be achieved in Fig. 1. (Power-spectrum analysis of smaller regions selected from the complete image shows that the upper portion of the image is defocused by about 4% less than is the lower portion.) When the blurring varies significantly from one part of the image to another, one can often select and separately restore smaller regions of the complete image over which the blur is sufficiently constant. In a few special cases, such as coma aberration of a spherical lens (Ref. 14), we can remove a spatially variant blur by applying a geometrical transformation to the image to make the blur spatially invariant, by restoring this image and by applying the inverse geometrical transformation.

Power-spectrum analysis will not always give sufficient information to determine the OTF of the blur. The MTF pattern may not be distinctive enough (for example, the MTF of blurring due to time-averaged atmospheric turbulence is almost gaussian), or it may be hidden by noise or by structure in the power spectrum of the original (unblurred) image. If we can correctly estimate the general type of blurring, by a priori knowledge or by inspection of the blurring of edges or points in the image for example, then its extent may be

obtained as illustrated in Fig. 2. Here, we assumed that the image was blurred in a defocused camera with a circular aperture. Then, we restored a 128- by 128-element region of the blurred image shown in Fig. 1(a) by using 16 values of assumed blur-circle diameter ranging from 0 mm (no restoration) to 0.75 mm (too much restoration) in 0.05 mm steps. An operator who views such a multiple-image display can choose the best restoration and, assuming spatially invariant blurring, restore the complete image in the same way. In this case, it is evident that the best restoration occurs for 0.65-mm blur circle diameter, in agreement with the power-spectrum analysis procedure. Only 55 seconds real time was required for the system to perform the 16 restorations and to display the results on the TV monitor.

We performed the above Wiener-filter restorations assuming that the original image had a constant signal-to-noise ratio equal to 30 dB. (The choice of a constant signal-to-noise ratio, rather than one which varies with frequency, has been discussed in Ref. 7). The use of a higher value of signal-to-noise ratio produces more restoration but at the expense of a noisier image and more severe artifact generation (e.g. due to film nonlinearity, a spatially variant blur, dust or scratches on the film etc.). In practice, it appears preferable to choose this value subjectively rather than to use the true average signal-to-noise ratio of the image. The signal-to-noise ratio of photographic film varies with film exposure, so that no single value will be correct for all regions of an image (Ref. 7). Furthermore, we often want to optimize the restoration of a particular feature, rather than the complete image, and this is best achieved interactively by trial and error.

FIGURE 2 - Determination of the OTF of a blur interactively. A region of a focus-blurred image was restored assuming 16 different blur-circle diameters. The values start at Ø mm (i.e. no restoration) (upper left) and increase in Ø.Ø5-mm steps to Ø.75 mm (lower right). A blur-circle diameter of Ø.65 mm gives the subjectively best restoration.

4.0 IMAGE ENHANCEMENT

4.1 Ad-Hoc Techniques

Image enhancement is harder to define than image restoration; there is usually no "ideal image" which the processing tries to achieve. Andrews (Ref. 16) has defined enhancement as the attempt to improve the appearance of an image for human viewing or subsequent machine processing.

The choice of an enhancement technique is simplified if the information of interest differs in some significant respect from the remainder of information in the image. Figure 3(a), for example, shows an aerial photograph of a flock of birds flying over water. We want to extract the birds (the numerous small white objects), so that a subsequent computer algorithm can count and analyze them. The spatial and gray scale characteristics of the birds are significantly different from those of the background. We first enhance the birds by high-pass filtering and then eliminate the background by setting any image element with a gray level below a fixed threshold to full black (Fig. 3(b)).

In the ballistic-range photograph shown in Fig. 3(c), the objective of the enhancement is to extract the horizontal and vertical reference lines and the projectile, so that a computer algorithm can measure the relative position and orientation of the projectile. We first apply a directional filter to select all horizontal and vertical lines and edges in the image. This eliminates the diagonal lines caused by shock waves and strongly attenuates other features. After high-pass filtering to enhance the sharp horizontal and vertical reference lines relative to the "softer" horizontal edges of the projectile and its shadow, we detect the reference lines by setting all image elements with a gray level exceeding a fixed threshold full white, and all others full

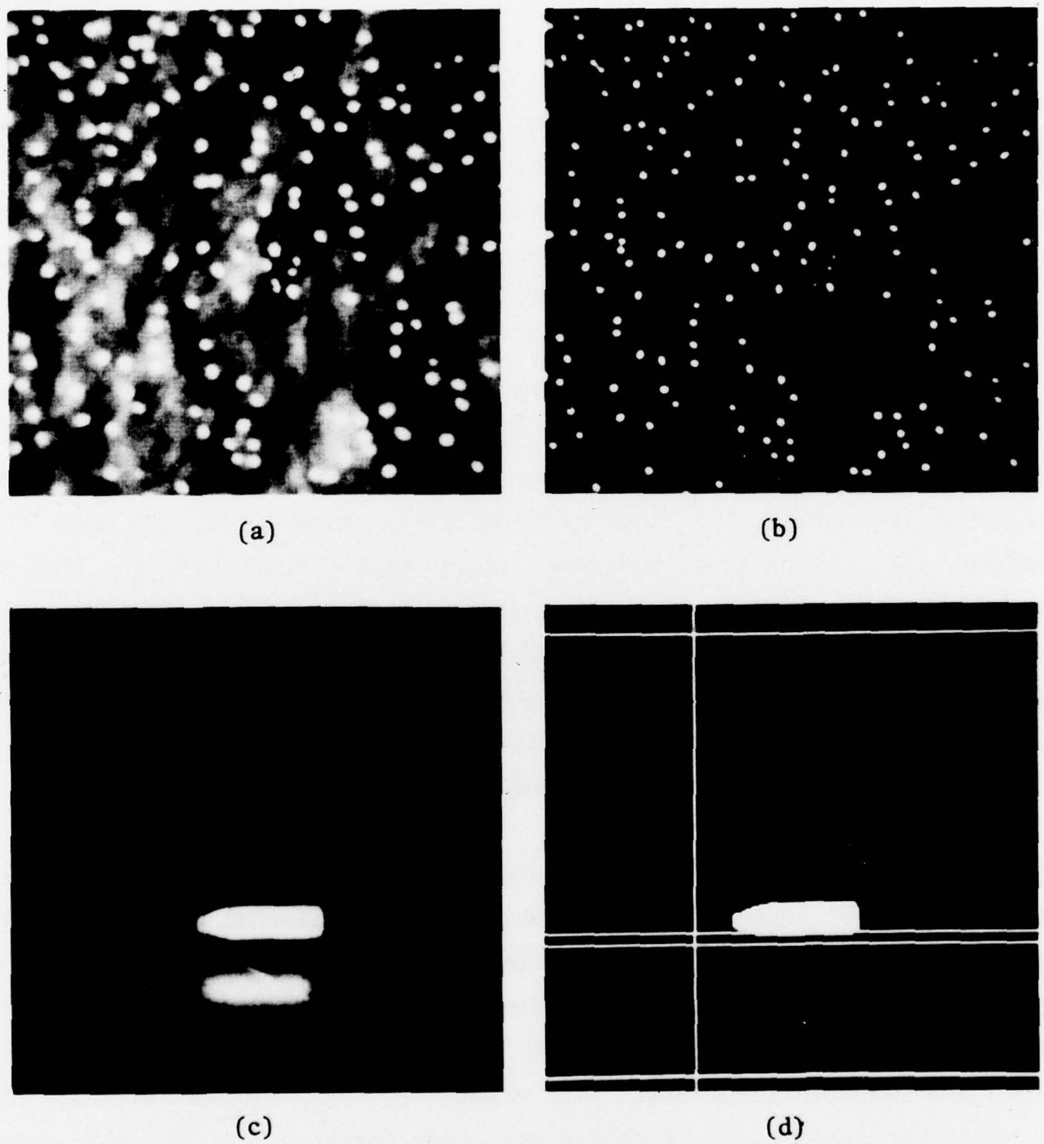


FIGURE 3 - Ad-hoc image enhancement. The two original images show an aerial photograph of a flock of birds (a), and a photograph of an artillery shell in a ballistic range (c). In both cases, the spatial and grayscale characteristics of the information of interest are significantly different from those of the background. This information can easily be enhanced by appropriate filtering, (b) and (d).

black. We similarly low-pass filter the original image to attenuate the reference and shock-wave lines and then apply threshold detection to produce an image which contains only the projectile. Figure 3(d) shows the result of adding the image containing the detected reference lines to the image containing the detected projectile.

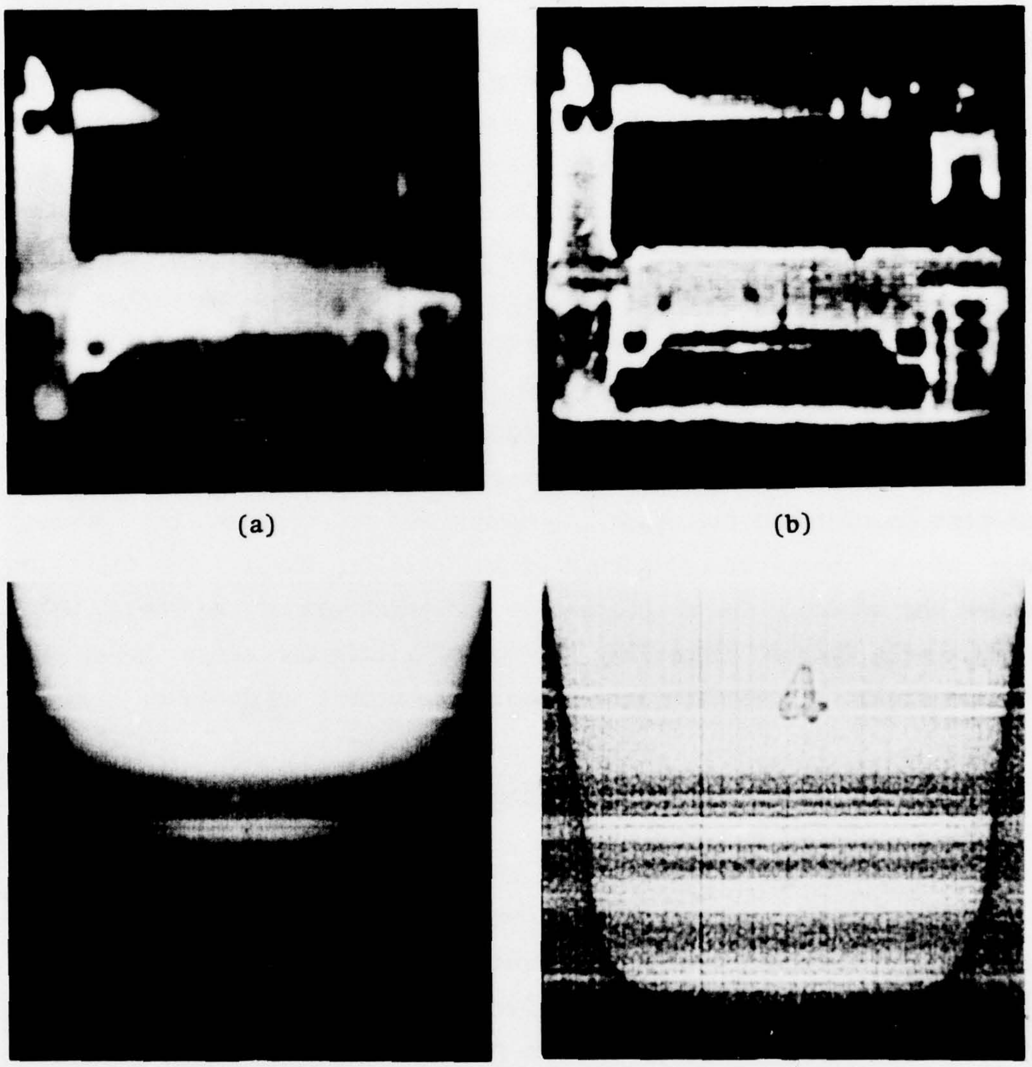
The above two examples took advantage of distinctive spatial and gray scale properties of the information of interest as they appeared in the final film images. A-priori knowledge of these properties, combined with interactive determination of the appropriate filtering procedures, allowed us to enhance the information of interest. In general, however, the images will be more complex than either of the above examples, and the information to be enhanced will not be as well differentiated from the background. In such cases, we should use all the information available in performing the enhancement. This includes all knowledge we have of the characteristics of the image-formation process, the imaging sensor, the image-recording medium and, if the image is intended for human interpretation, the display system and the properties of the human visual system.

A unified approach to image enhancement which includes these, and possible other significant factors, has yet to be established. Most enhancement techniques, such as those illustrated in Fig. 3, are ad hoc and are not based on how the image to be enhanced was produced. We next illustrate how two of the above factors, considered separately, can be applied to image enhancement. Section 4.2 shows how the properties of the image-formation process can enter into the enhancement problem, while Sec. 4.3 describes an enhancement technique based on the characteristics of human vision.

4.2 Enhancement Based on the Image Formation Process

Oppenheim et al (Ref. 17) have described homomorphic filtering as a technique for separating signals into additive parts and enhancing the parts of interest compared to those of less interest. They showed how a visible-light image, which is assumed to be formed by multiplying an illumination part by a part due to target reflectivity, can be enhanced by reducing the contrast caused by changes in illumination and increasing the contrast due to changes in reflectivity. In their example, the homomorphic filtering consisted in calculating the logarithm of the image to make the illumination and reflectivity parts additive, high-pass filtering to attenuate the low-frequency illumination part relative to the higher frequency reflectivity part, and then exponentiating. As we illustrate in the next two paragraphs, a similar type of homomorphic filtering may be used to enhance images formed by the emission of infrared radiation, as well as certain kinds of images formed by the transmission of X or gamma radiation.

An image formed by the emission of infrared radiation consists of a part which depends on target temperature multiplied by the emissivity of the surface. Because of thermal conduction within the target, the temperature-dependant part may show a less sharp image of the target than the emissivity part. For targets at close range where this limits the resolution, we may be able to sharpen the target image by using multiplicative homomorphic filtering to attenuate the lower frequency temperature-dependant part. Figures 4(a) and (b) show the result of applying this filter to an infrared image formed in the 9- to 13-μm band. As well as sharpening the image, the filtering has compressed the dynamic range by reducing contrast due to both changes in target temperature and surface emissivity which vary slowly from one region of the image to another.



(a) (b)

(c) (d)

FIGURE 4 - Image enhancement based on a knowledge of how the image was formed. Figures (b) and (d) show, respectively, compression of the dynamic range of an image formed by emission of infrared radiation (a), and an image formed by transmission of gamma radiation (c).

Images formed by the exponential absorption of radiation may also require multiplicative homomorphic filtering. Suppose we take separate radiographs of two objects (or of two slices of the same object). If the two objects are superimposed, and a third radiograph is taken, the result will be the product, not the sum, of the individual radiographs. Consider the simple case where the first object contains a single low spatial-frequency component, the second contains a single high spatial-frequency component, and we want to filter the composite radiograph to remove one of the frequency components. Unless we first calculate the logarithm to make the two frequency components additive, linear filtering may not be able to remove the sum and difference frequencies produced when the two frequency components are multiplied (Ref. 6). Figures 4(c) and (d) illustrate the use of multiplicative high-pass homomorphic filtering to enhance and to compress the dynamic range of a gamma-ray radiograph of an artillery shell. The filtering reduces the contrast due to changes in the thickness of the shell, which covers a wide dynamic range but presents little interest here, and enhances higher frequencies corresponding to cracks or defects.

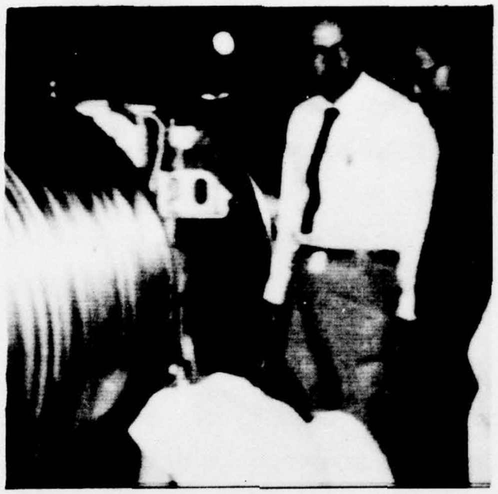
4.3 Enhancement Based on the Properties of Human Vision

High-pass spatial filtering, such as that described in Sec. 4.2, is an effective way to compress the dynamic range of an image and to sharpen or enhance low-contrast details. This processing can preserve information that might otherwise be lost due to an inadequate display medium (e.g. a TV monitor, a halftone printing process, etc.). However, it often introduces artifacts which are easy to misinterpret. We cannot be sure if what we see in the filtered image is true, or if it was introduced by the processing.

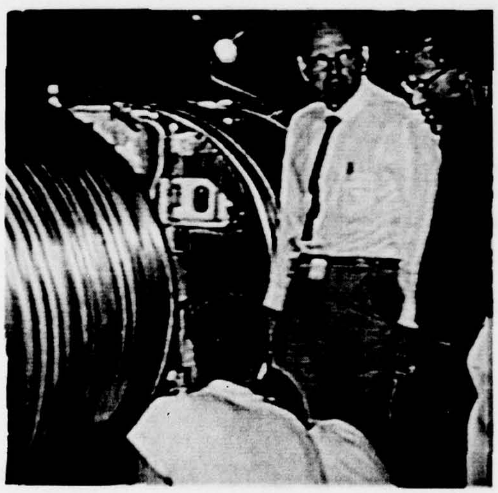
The human eye compresses the dynamic range of visual information by high-pass filtering before sending it along the optic nerve to the

brain. It is reasonable to assume that the brain decodes this information to attempt to restore to the original image. Certain visual illusions, such as the Cornsweet illusion (Ref. 18), suggest that this indeed happens. The basis of the present enhancement is to filter the image in the same way as the eye performs dynamic range compression. At best, the brain may be able to partially restore to the original image. At worst, the brain may be less likely to misinterpret artifacts generated by this filtering than those generated by other types of high-pass filtering; the same artifacts will be generated later by the eye anyway.

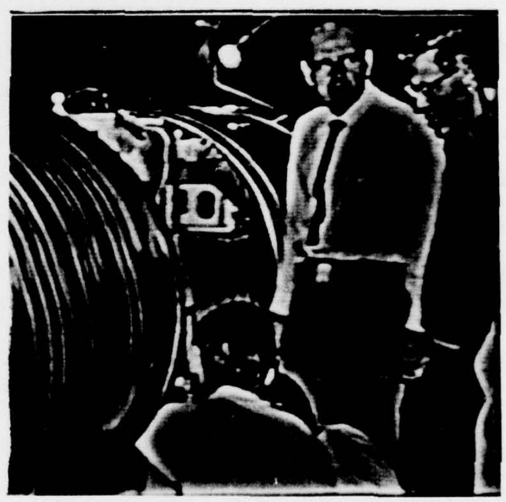
Figure 5 shows the result of enhancing an image using the nonlinear model for the eye proposed by Hall and Hall (Ref. 19) . In this model, the image is assumed to be low-pass filtered by the lens of the eye, logarithmically detected by receptors in the retina, and then high-pass filtered by lateral inhibition between neighboring receptors. The two enhanced images shown in Figs. 5(b) and (c) correspond, respectively, to low-frequency responses measured by Davidson (Ref. 20) for the visual systems of subjects BM and LF. The frequency scaling is such that the 7-cm square processed images should be viewed at a distance of approximately 25 cm. Images that have been enhanced in this way are similar in overall appearance to the original, but the contrast in both light and dark areas has been increased and high-frequency details have been sharpened.



(a)



(b)



(c)

FIGURE 5 - Image enhancement based on the properties of human vision. Figures (b) and (c) illustrate compression of the dynamic range of the original image (a) by filtering according to a simple model for the human visual system. The two enhanced images correspond to the frequency responses of the visual systems of two individuals.

5.0 CONCLUSIONS

We have described an interactive digital image-processing system based on a PDP 11/40 minicomputer. It includes on-line facilities for digitizing film, for TV display and for recording images on film. An array transform processor interfaced to the minicomputer allows complex processing operations, such as 2D FFT filtering, to be interactively applied in several seconds to images containing 256 by 256 elements.

Such a system has numerous applications in the general area of 2-dimensional signal processing. We have outlined 2 current applications involving the improvement of images intended for human interpretation, in particular, interactive image deblurring and enhancement. Interactive processing allows us to optimize the restoration or enhancement of features of special interest in the image, whereas normally the processing is suited to the average properties of the image. In addition, it often permits easier detection of artifacts generated by the processing, and gives us a better overall understanding of what effect the processing has on the image.

The deblurring was achieved by analyzing the image to identify the type and the extent of degradation, and then restoring the image by inverse Wiener filtering. We gave an example of interactive analysis and restoration of a photograph blurred by an out-of-focus camera. The enhancement was achieved in 3 ways: through ad-hoc processing , by taking account of the image-formation process, or by including the properties of human vision. We gave 4 examples illustrating the enhancement of images formed by the reflection of visible light, emission of infrared radiation and the transmission of gamma radiation.

6.0 ACKNOWLEDGEMENTS

The author wishes to thank Mr. P. Boutin for his valuable help in developing and in implementing the interactive system. The work of Mr. A. Blanchard in devising the Bessel function routine and of Mr. C. Munteanu in interfacing the video digitizer is also gratefully acknowledged.

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APPENDIX A

Description of the Image-Processing Operating System

In this appendix we briefly describe how a user controls the DREV image-processing system by giving interactive commands on a teletype and by setting switch-selected options.

The first step in using the system is to select the desired processing options by setting bits on the switch register of the PDP 11/40 console. If the switch register is not set, then the operator must provide this information by replying to questions on the teletype whenever a processing operation that uses these options is executed.

The main options to be selected are the size of the working image and that of the display area. The size of the working image represents the size of the image stored in the core or disk memory that is to be processed. Setting bit 3 of the switch register selects a 128- by 128-element image, setting bit 4, a 256- by 256-element image and setting bit 5, a 512- by 512-element image. Images containing 128 by 128 elements or 256 by 256 elements are stored in the 65 kword data memory of the array transform processor, while images containing 512 by 512 elements are stored in one of 4 files in the disk memory. For 128- by 128-element images, the user must reply to a question on the teletype to specify which of the 4 images in the array processor data memory he wishes to process. Similarly, the user must specify one of the 4 disk files when he is processing 512- by 512-element images.

The television monitor displays a total area of 512 by 512 elements. A user wishing to view simultaneously several smaller images on the display rather than a single one containing 512 by 512 elements

selects the desired display size by using the switch register. The area that the image will occupy on the display is set to 128 by 128 by setting bit 6 of the switch register, to 256 by 256 by setting bit 7, and to 512 by 512 by setting bit 8. The size of the display area need not be equal to the size of the working image. For example, setting bits 3 and 7 will cause a 128- by 128-element image to be displayed on a 256- by 256-element display area, whereas setting bits 3 and 8 will cause the 128- by 128-element image to fill the complete display area. If bit 9 of the switch register is set and the display area is 128 by 128 or 256 by 256, then the new image is stored in the display position one beyond the last stored image. When the display area is full, or if the selected display area is 512 by 512, then the display is erased before the new image is written.

When the desired options have been set on the switch register, image-processing commands can be given interactively on the teletype. The system types an asterisk (*) to indicate that it is ready to accept a command from the user. These commands are in the form of integer numbers containing 4 digits or less. In some cases, such as the 2-dimensional FFT of a 256- by 256-element image, the system will immediately execute the operation and return to the command mode. In other cases, such as filtering operations that require parameter specification, the user must reply to questions on the teletype before the processing will proceed.

The first digit of each integer command number describes the general class of the operation. There are currently 9 classes of operations corresponding to the first digits 1 to 9:

1 = display operations
2 = input/output operations
3 = FFT operations

4 = gray scale normalization

5 = mathematical operations

6 = frequency-domain filters

7 = pattern generation

8 = geometrical operations

9 = miscellaneous operations

For example, any command that begins with a 1 is a display operation, whereas any command that begins with a 6 is a frequency-domain filtering operation. The remaining digits of the command number define the specific operation in each class. For example, in the class of display operations, command "11" displays an image on the television monitor while command "16" graphs a selected row of an image. In the class of frequency-domain filtering operations, command "612" multiplies the working image (which in this case must be a 2-dimensional FFT) by the filter required to restore a particular type of focus blurring. A listing of the available commands is given in Appendix B.

In addition to the working image, two 512-word integer buffers are accessible to the user. The "IZT" buffer contains the display transfer function, i.e. the function that maps the stored gray scale values to displayed gray levels. This transfer function is specified with command "99". Other operations, such as the geometrical transformation specified by command "85" and the frequency-domain filter specified by command "661", also use the function stored in this buffer. The second buffer ("IZ") is used for temporary storage of information, such as the gray scale histogram calculated with command "55". This buffer is also used as a working area and most processing operations will alter its contents.

APPENDIX B

Listing of Interactive Commands

When the system prompts by typing an asterisk (*) on the teletype, then it is ready to receive one of the following commands:

```
**********************************

  ***** PEP SCAN CONVERTER DISPLAY OPERATIONS *****

COMMAND          OPERATION

  10        CLEAR TV DISPLAY
  11        DISPLAY AN IMAGE
  12        DISPLAY A SERIES OF IMAGES ON DISK
  15        GRAPH A BUFFER
  16        GRAPH A ROW
  171       LIST A BUFFER ON LP
  172       LIST A REGION ON TTY
  173       LIST A REGION ON LP

**********************************

***** INPUT/OUTPUT OPERATIONS *****

COMMAND          OPERATION

  20        READ IMAGE ON MT
  201       READ AND REFORMAT N BY M IMAGE ON MT
  21        WRITE IMAGE ON MT
  22        REWIND MT
  231       TV DIGITIZE (CORRECT FOR 4:3 ASPECT)
  232       TV DIGITIZE (512X480, NO CORRECTION)
  233       DIGITIZE POINT ON TV AS SET BY TRACKBALL
  241       MOVE 128 IMAGE IN A.P.
  242       MOVE 512 IMAGE ON DK2
  25        READ IMAGE ON DK2
  26        WRITE IMAGE ON DK2
  271       READ G.S. TRANSFER FUNCTION ON DK2
  272       WRITE G.S. TRANSFER FUNCTION ON DK2
  273       READ G.S. HISTOGRAM ON DK2
  274       WRITE G.S. HISTOGRAM ON DK2
  275       MOVE IZT BUFFER TO P BUFFER
  276       MOVE P BUFFER TO IZT BUFFER
  277       CONVERT P BUFFER TO INV WIENER FILTER
  278       GENERATE HALLS MODEL FOR HVS IN P BUFFER
```

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***** FFT OPERATIONS *****

COMMAND	OPERATION
30	2D FFT
31	INVERSE 2D FFT
321	MULTIPLY ONE FFT BY ANOTHER
322	MULTIPLY ONE FFT BY CC OF ANOTHER
35	MODULUS OF AN FFT
36	CALCULATE 1-D AMPLITUDE SPECTRUM OF IMAGE
37	CONVERT FFT TO INVERSE WIENER FILTER

****

***** GRAYSCALE NORMALIZATION *****

COMMAND	OPERATION
401	NORMALIZE (32767 MAX)
402	NORMALIZE (0 TO 32767)
411	CLIP (G.S. UNITS)
412	CLIP (UNITS OF ST DEVS)
413	CLIP AND NORM (G.S. UNITS)
414	CLIP AND NORM (UNITS OF ST DEVS)

****

***** MATH OPERATIONS *****

COMMAND	OPERATION
501	LOGARITHM
502	EXPONENTIATE
511	ADD ONE IMAGE TO ANOTHER
512	SUBTRACT ONE IMAGE FROM ANOTHER
513	MULTIPLY ONE IMAGE BY ANOTHER
514	DIVIDE ONE IMAGE BY ANOTHER
521	ADD A CONSTANT TO A REGION
522	MULTIPLY A REGION BY A CONSTANT
53	TRANSFORM USING G.S. TRANSFER FN
54	COMPLIMENT GRAYSCALE
55	G.S. HISTOGRAM (IZ BUFFER)
561	CALCULATE MIN AND MAX VALUES
562	CALCULATE MEAN AND RMS VALUES
571	2X2 EDGE DETECTOR (SQR)
572	2X2 EDGE DETECTOR (ABS)
58	DIRECTION OF STRUCTURES TO GRAY LEVEL
591	MAD CORRELATION
592	MATHEMATICAL CORRELATION
593	SSDA CORRELATION

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 ***** FREQUENCY-DOMAIN FILTERS *****

COMMAND          OPERATION

  601       MOTION DEGRADE
  602       MOTION RESTORE
  611       FOCUS DEGRADE
  612       FOCUS RESTORE
  621       HIGH-PASS: F(W)=SQRT(W)
  622       HIGH-PASS: F(W)=W
  623       HIGH-PASS: F(W)=W**2
  641       LOW-PASS (EXP CUTOFF)
  642       HIGH-PASS (EXP CUTOFF)
  661       FILTER WITH LOOKUP TABLE IN IZT BUFFER
  662       FILTER WITH LOOKUP TABLE IN P BUFFER
  681       HVS LOW-PASS (HALLS MODEL)
  682       HVS HIGH-PASS (HALLS MODEL)

*********************************

    ***** PATTERN GENERATION *****

COMMAND          OPERATION

  711       DRAW A GRAYSCALE CHART
  712       DRAW G.S. CHARTS TO LEFT OF IMAGE
  721       DRAW A GRID
  722       DRAW A BOX AROUND A REGION
  723       DRAW DIVIDING LINES BETWEEN IMAGES
  724       DRAW A CROSS AT HIGHEST POINT
  731       GENERATE A GRAYSCALE CHART
  732       GENERATE A PATTERN OF SQUARES
  733       GENERATE A PATTERN OF RANDOM NOISE
  734       GENERATE A CONSTANT LEVEL
  77        SET IMAGE TO ZERO

*********************************

***** GEOMETRICAL OPERATIONS *****

COMMAND          OPERATION

  801       MAGNIFY A REGION
  802       MINIFY A REGION
  803       READ 128 REGION OF 512 IMAGE
  804       READ 256 REGION OF 512 IMAGE
  805       READ SPECIFIED REGION OF 512 IMAGE
  806       WRITE SPECIFIED REGION OF 512 IMAGE
  82        TRANSPOSE
  83        REVERSE X AXIS
  841       SCROLL IMAGE HORIZONTALLY
  842       SCROLL IMAGE VERTICALLY
  85        GEOMETRICAL TRANSFORM (T.F. IN IZT BUFFER)
```

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**********************************

     ***** MISC OPERATIONS *****

COMMAND         OPERATION

  900       INTRODUCTORY INFO ON SYSTEM COMMANDS
  901       INFO ON DISPLAY COMMANDS (THESE START WITH 1)
  902       INFO ON I/O COMMANDS (THESE START WITH 2)
   :
  909       INFO ON MISC COMMANDS (THESE START WITH 9)
  93        MATCH OPPOSITE EDGES OF IMAGE
  94        RADIAL DIST FN (P BUFFER)
  99        GENERATE G.S. TRANSFER FN
  999       EXIT TO PDP 11/40 MONITOR

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"Interactive Digital Image Restoration and Enhancement"
by J.F. Boulter

We describe an interactive digital image-processing system that includes a minicomputer, a programmable array transform processor and on-line image digitizing and display equipment, and illustrate typical applications in the areas of image restoration and enhancement. A photograph blurred by a defocused camera is analyzed to determine the nature of the blur and is restored. Image-enhancement techniques, based on the properties of human vision or on the image-formation process, are applied to visible light, infrared and radiographic images. (U)

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